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INFLUENCE OF OPERATION PATTERNS OF LIGHT-DUTY FREIGHT VEHICLES ON NOx POLLUTION AT LOCAL ROADSIDES

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ABSTRACT–Running tests on roads were conducted to clarify the influences of road infrastructure, traffic condition and vehicle's emission level to the amount of emission at local roadsides, and to reveal the operation patterns which can reduce the emission peaks. NOx emission peaks of two light duty freight diesel vehicles which have different emission levels were evaluated by using an on-board measurement system. Tests were carried out with various payload conditions and road conditions. As a result many NOx emission peaks were observed when the vehicles were starting or accelerating at intersections. The test vehicle which has higher emission level caused higher frequency and level of NOx emission peaks. Shifting up at lower engine speed in combination with lower acceleration brought out not only reduction of NOx emission peaks level but also of CO_2 mass emission.

KEY WORDS : Truck, Diesel engine, Acceleration, Road test, Pollution, Emission

1. INTRODUCTION

In recent years, emissions per diesel vehicle have been reduced substantially due to the successive strength of automotive emission regulations. However, environmental standards are still unachieved in many areas mainly at urban roadsides, and improvement of air quality at local roadsides is considered to be a pressing issue to be solved. One of the causes of air pollution at local roadsides is attributed to growth of traffic volume resulted from the increased number of vehicles owned. It is assumed that major emission peaks observed at vehicle acceleration, which occur frequently at drives on roads, also have some influence on air pollution at local roadsides. Various studies on air pollution at local roadsides have been performed (Oguchi *et al.*, 1995; Morino *et al.*, 1997; Kobayashi *et al.*, 2000; Takada *et al.*, 2002). However the reason and degree of the emission peaks, and the traffic conditions in which the emission peaks occur have not been clarified, nor the amount of influence of engine emission characteristics on the emission peaks at local roadsides. Major factors that affect the frequency and level of emission peaks are external factors such as road infrastructure and traffic environment, driving factors such as drivers' operating patterns and characteristics, and technical factors such as vehicles' emission levels.

This research aims to clarify the influences of road infrastructure, traffic condition and vehicle's emission level to the amount of emission at local roadsides by conducting running tests on roads paying attention to the factors mentioned above, and to reveal the operation patterns which can reduce the emission peaks.

The test was conducted with two light-duty freight vehicles, both have payload of 2 tones and have different emission regulation levels. Instantaneous NOx emission, vehicle condition and engine condition were measured by a real time on-board measurement system, and road infrastructure and traffic condition were recorded by VTR.

From the obtained results, factors that causes NOx emission peaks were analyzed by examining the relations between road infrastructures, traffic environment and the frequency and levels of NOx emission peaks, as well as the relations between the level of emission regulation of the vehicles and the frequency and level of NOx emission peaks. Operation patterns to reduce CO_2 emission are also revealed by this research.

2. TEST CONDITIONS

2.1. Specifications of Test Vehicles

Two light duty freight vehicles, which have different exhaust emission levels, were tested for this research. Their outline pictures are shown in Figure 1, and main

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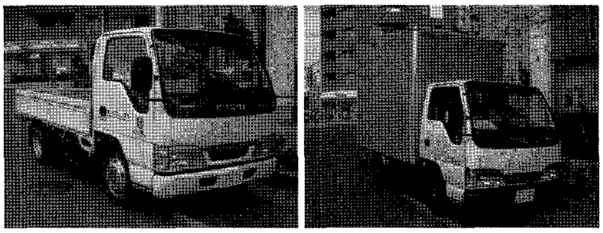

Figure 1. Outline picture of test vehicles.

Table 1. Main specifications of test vehicles

Item		Vehicle 1	Vehicle 2
Length	(mm)	4,680	4,990
Width	(mm)	1,690	1,880
Height	(mm)	1,960	2,940
GVW	(kg)	4,485	4,675
VW	(kg)	2,320	2,510
Max. payload (kg)		2,000	←
Engine type		4HL1	4HF1
Cyl. arrangement		Inline-4	←
Aspiration		Natural	←
Swept volume (cm^3)		4,777	4,334
Compression ratio		18.5	←
Max. power (kW/rpm)		96/3,000	81/3,100
Max. torque (Nm/rpm)		333/1,500	275/1,500
Fuel injection system		Common rail type	Distributor type
EGR system		Cool	Hot
Catalyst		Ox. catalyst	w/o
Transmission		5-speed	←
Final ratio		4.777	←
NOx	(g/kWh)	3.18(3.38)	4.20(4.50)
CO	(g/kWh)	2.19(2.22)	3.10(7.40)
HC	(g/kWh)	0.44(0.87)	1.50(2.90)
PM	(g/kWh)	0.17(0.18)	0.21(0.25)

Note: The test cycle for exhaust emissions is Japanese D13. The parentheses in the emission columns indicate the emissions regulations.

specifications are shown in Table 1. One test vehicle shown in the left side of Figure 1 is mounted with the direct injection diesel engine with 4 cylinders, which output is 96 kW and swept volume is 4.8 liter. This vehicle, called as "Vehicle 1" in this paper, equips with a common-rail injection system, a cooled EGR system and an oxidation catalyst for exhaust emissions reduction, and adapts to 2003 Japanese emission regulation. Vehicle 1 registration was in August 2004, and the mileage was about 2,800 km at the time of examination.

The other test vehicle shown in the right side of Figure 1 is also mounted with the direct injection diesel engine with 4 cylinders, however its output and swept volume are rather small. This vehicle, called as "Vehicle 2" in this paper, equips with a hot EGR system for exhaust emissions reduction, and adapts to 1998 Japanese emission regulation. Vehicle 2 registration was in March 2000, and the mileage was about 10,160 km at the time of examination.

2.2. Outline of Test Courses

In order to evaluate NOx emission in various traffic conditions, two routes were selected as the test courses which included an urban trip in a city, a suburban trip and a highway trip. The authors defined single lane roads and narrow roads as urban roads where a large volume of traffic or obstacles such as parked vehicles often cause traffic congestion, two lanes roads as suburban roads where traffic flow is relatively smooth, and driveways of speed limit 100 km/h as highways.

One test course is in the west area of Tokyo, called below as "Tokyo course", which distance is about 51.8 km, and with relatively flat roads. Tokyo course includes an urban trip, two suburban trips and a highway trip, their trip distances are about 8.5 km, 32.8 km and 10.5 km respectively. The urban trip of Tokyo course does not include any narrow road.

The other test course is in Yokohama city, called below as "Yokohama course". Yokohama course is consisted of only an urban trip, but including some narrow roads and some slopes like an overpass, and its total distance is about 17.5 km. The features of the test courses are shown in Table 2 and 3.

2.3. Payload and the Other Test Conditions

The tests were performed for 9 days, between December

Table 2. Outline of Tokyo course.

Route	Distance (km)	Lane	Traffic light	Turn
Suburban trip-1	13.5	2	35	3
Highway trip	10.5	2	0	0
Urban trip	8.5	1	35	3
Suburban trip-2	19.3	2	40	3
Total	51.8	–	110	9

Table 3. Outline of Yokohama course.

Route	Distance (km)	Lane	Traffic light	Turn
Urban trip*	17.5	1	79	36

*Including narrow roads

Table 4. Payload conditions of Vehicle 1 and Vehicle 2.

Payload Condition	Vehicle 1			Vehicle 2		
	Pay load (kg)	GVW (kg)	N	Pay load (kg)	GVW (kg)	N
Heavy	2,000	4,485	2	2,000	4,675	1
Medium	1,000	3,485	2	1,000	3,675	1
Light	0	2,485	2	0	2,675	1

N: number of test runs

13 and 24, 2004.

Payload was set to full loading, half loading and light loading. The payload conditions are shown in Table 4.

A commercial diesel fuel of 50 ppm sulfur content was used for the examination. It was supplied at the same filling station in order to minimize the influence to NOx emission.

The same driver operated the test vehicles in all the runs to eliminate the effect of driver's characteristics.

2.4. Exhaust Emissions Measurement System

In this study, on-board measurement system was employed to evaluate NOx emission of the test vehicles in real traffic conditions.

2.4.1. Outline of measurement system

NOx mass emission can be obtained by a measurement of exhaust gas flow volume and NOx concentration, and some on-board measurements for NOx from diesel trucks have been conducted using the CVS system. However, those systems are often too large for an easy installation for on-board NOx measurement (Yokota *et al.*, 1989; Norbeck *et al.*, 2001). Therefore, the simple measurement system for NOx emission is considered here.

In this system, NOx mass flow can be calculated based on the NOx concentration data measured by a zirconia sensor, the calculated air flow based on engine speed and engine volumetric efficiency. It is reported that the accuracy of NOx measurement sensors using this system is adequate, as compared to the CVS system (Tahara *et al.*, 2002). This simple method was applied in our past studies (Takada *et al.*, 2004; 2005), and is also used in this research.

Table 5 shows the items measured in this study. These items were measured every 0.5 second except for the vehicle position which was measured every 1.0 second. The vehicle position by GPS and the VTR picture were recorded to specify the roadsides where intensive NOx emission was observed.

Notations, units and meanings related to NOx emission are listed in Appendix 1. NOx mass emission per running distance is generally taken as a NOx emission factor; for instance, the NOx emission factor for the test course means NOx mass emission (g) per one kilometer in the specified trip and is referred to as $E_{NOx,X,TR}$. The instantaneous NOx emission factor is described by a value of NOx mass flow (g/h) divided by the vehicle speed (km/h) measured every 0.5 second and is referred to as $E_{NOx,X,Inst}$. The same definition and notation are applied to the description of the vehicle speed and CO_2 emission.

2.4.2. Accuracy of NOx emission measurement

Before conducting the examinations on roads, the accuracy of NOx emission measurement was verified at a test bench. JE05 mode test cycle and Diesel 10/15 mode test cycle were used for the verification. The test results are shown in Table 6, where NOx emissions of the on-board measurement system and the CVS system are described. The difference in NOx emission factors between the on-board system and the CVS system were within 5%. These results demonstrate that this system has sufficient accuracy for NOx emission measurement in real world conditions.

Table 6. Measurement accuracy of on-board system.

Test mode	Measurement system	NOx (g/km)	Ratio
JE05M	On-board	1.11	1.046
	CVS	1.06	
D10/15M	On-board	1.94	1.032
	CVS	1.88	

Table 5. Measured items by on-board measurement system.

Item	Equipment	Notation	Unit	Accuracy
NOx concentration	Zirconia sensor	C_{NOx}	ppm	Within ±10%
Air excess ratio	Zirconia sensor	λ	–	Within ±10%
Engine speed	ECU	Ne	rpm	–
Vehicle speed	ECU	V_{Inst}	km/h	–
Vehicle position	GPS	–	–	–
Picture	VTR	–	–	–

3. TEST RESULTS

3.1. Test Results for Large Areas

For the prevention of air pollution caused by vehicle over a large area, the total amount of emissions from vehicles needs to be decreased. For this purpose, comparison between Vehicle 1 and Vehicle 2 was performed about the amount of NOx and CO_2 emissions.

Table 7 shows the summary of test results concerning NOx emission factor and CO_2 emission factor of Vehicle 1 and Vehicle 2. NOx emission factor and CO_2 emission factor of Yokohama course were about 25% and 30% higher than those of Tokyo course respectively, namely the lower vehicle speed of Yokohama course caused higher emissions. NOx emission factor and CO_2 emission factor of Vehicle 1 were approximately 20% and 5% lower than those of Vehicle 2.

3.2. Test Results for Local Roadsides

It is assumed that major NOx emission peaks also have some influence on air pollution at local roadsides. The reason and degree of the NOx emission peaks, and the traffic conditions in which NOx emission peaks occur have not been clarified, nor the amount of influence of engine emission characteristics on NOx emission peaks at local roadsides. Therefore NOx emission peaks are analyzed in this research.

3.2.1. Maximum level and frequency of NOx emission peaks

Figure 2 shows maximum level and frequency of NOx emission peaks of Vehicle 1 and Vehicle 2 by each trip of the test courses. The NOx emission peak is defined as the peak value of NOx emission factor more than 10 g/km in this research. The frequencies of the NOx emission peaks of the both vehicles were highest in the urban trip, and they grew smaller by increasing average vehicle speed. The maximum levels of NOx emission peaks became larger by increasing payload, however no significant difference of the maximum levels was observed among the three traffic conditions. No NOx emission peak was observed on the highway cruising except for the vehicle starting at the entrance gate. The maximum levels of the NOx emission peaks reached more than 10 times as much as the average NOx levels shown in Table 7. The maximum level and frequency of the NOx emission peaks of Vehicle 2 were higher than those of Vehicle 1.

3.2.2. Analysis of conditions of NOx emissions peaks occurring

Some analyses were performed for the urban trip with paying attention to Vehicle 1, since the urban trip tests caused the highest frequency of NOx emission peaks in the test courses, which should influence on air pollution at local roadsides, and Vehicle 1 is more popular than Vehicle 2.

The occurrence points of the NOx emission peaks of Vehicle 1 under medium payload condition in Yokohama

Table 7. Summary of test results.

Test No.	Date	Course	Vehicle	GVW (kg)	Speed (g/km)	NOx (g/km)	CO_2 (g/km)
T-1	12/13/04	Tokyo	Vehicle 1	2,485	22.8	1.55	230
T-2	12/13/04	Tokyo	Vehicle 1	2,485	24.3	1.46	220
T-3	12/14/04	Tokyo	Vehicle 1	3,485	22.6	1.76	257
T-4	12/14/04	Tokyo	Vehicle 1	3,485	24.1	1.57	237
T-5	12/15/04	Tokyo	Vehicle 1	4,485	25.7	2.00	284
T-6	12/15/04	Tokyo	Vehicle 1	4,485	23.4	1.87	280
T-7	12/16/04	Yokohama	Vehicle 1	4,485	15.8	2.27	352
T-8	12/16/04	Yokohama	Vehicle 1	4,485	13.4	2.64	383
T-9	12/17/04	Yokohama	Vehicle 1	3,485	13.7	2.47	319
T-10	12/17/04	Yokohama	Vehicle 1	3,485	13.6	2.62	335
T-11	12/17/04	Yokohama	Vehicle 1	2,485	12.8	1.77	341
T-12	12/20/04	Yokohama	Vehicle 1	2,485	18.2	1.34	286
T-13	12/22/04	Tokyo	Vehicle 2	4,675	24.6	2.74	292
T-14	12/23/04	Tokyo	Vehicle 2	3,675	30.2	2.09	246
T-15	12/24/04	Tokyo	Vehicle 2	2,675	23.0	1.55	253
T-16	12/23/04	Yokohama	Vehicle 2	3,675	13.8	2.59	350
T-17	12/24/04	Yokohama	Vehicle 2	2,675	10.0	2.24	360
T-18	12/24/04	Yokohama	Vehicle 2	4,675	16.8	3.03	349

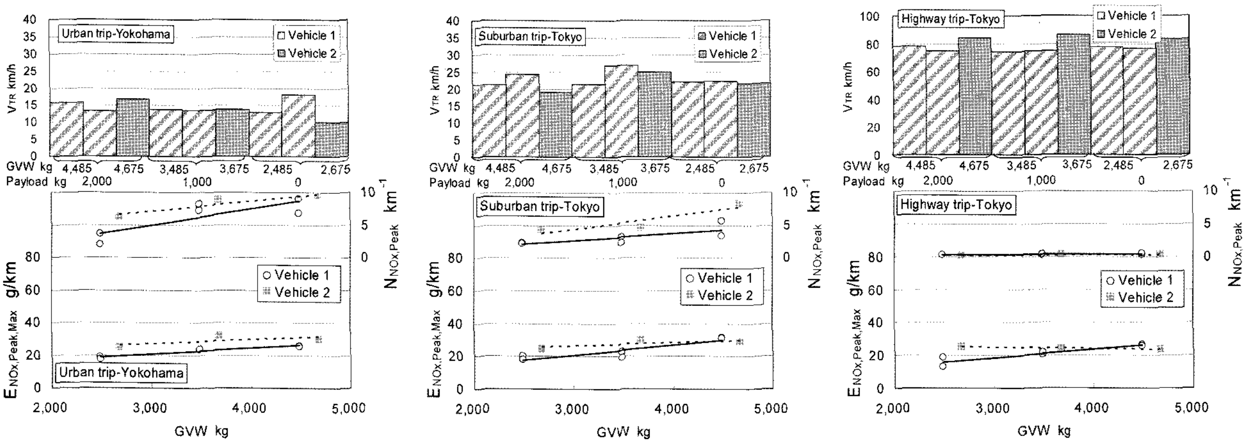

Figure 2. Maximum level and frequency of NOx emission peaks of Vehicle 1 and Vehicle 2 by each trip.

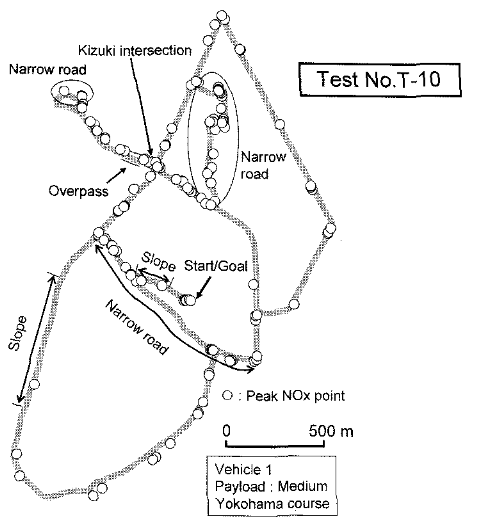

Figure 3. The occurrence points of the NOx emission peaks of Vehicle 1 under medium payload in Yokohama course.

course is shown in Figure 3. Many NOx emission peaks were observed at intersections and on narrow roads.

The conditions caused the NOx emission peaks were analyzed in detail. Approximately 70% of total number of NOx emission peaks appeared at intersections, where all vehicle dynamic conditions were under acceleration or at starting as shown in Figure 4. Then the gear positions of the transmission were almost in the second or the third. The major factor of road infrastructure which brought out the vehicle deceleration and stops was the existence of intersections. In addition, obstacles such as people, a bicycle and a parked vehicle at roadsides were one of the reasons as traffic environment.

3.2.3. Relationship between gear position and NOx emission factor

The relationship between gear position and instantaneous NOx emission factor of Vehicle 1 under medium payload condition was analyzed as shown in Figure 5. In order to clarify it the data of the neutral gear position and the

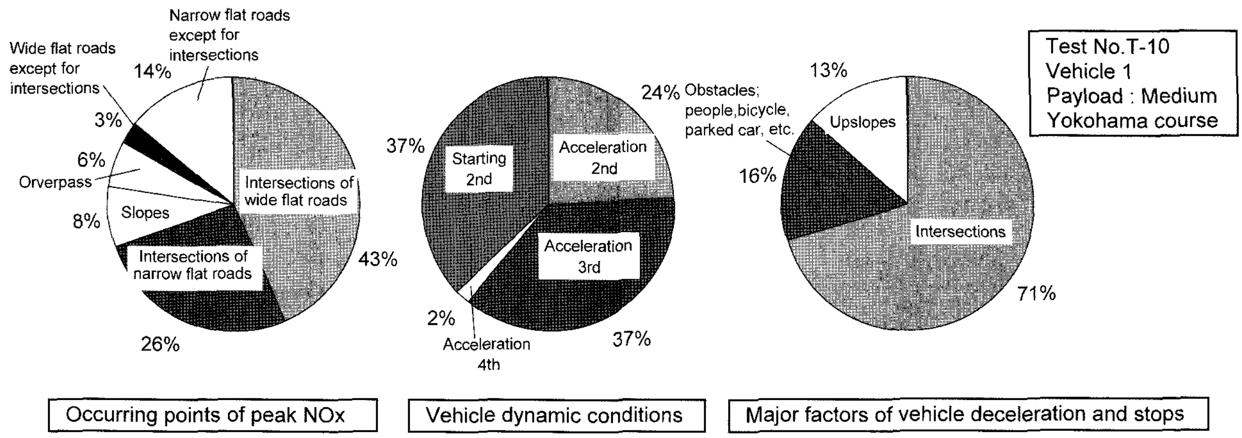

Figure 4. Analysis of conditions at NOx emission peaks occurring.

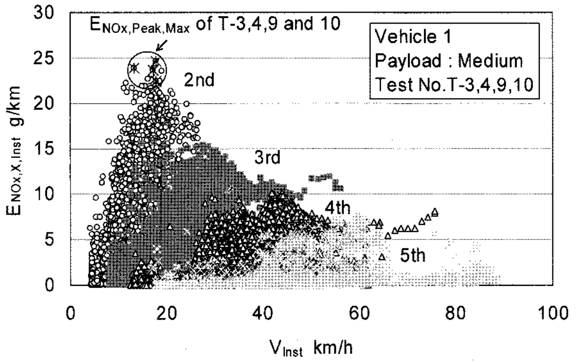

Figure 5. Relationship between gear position and NOx emission factor.

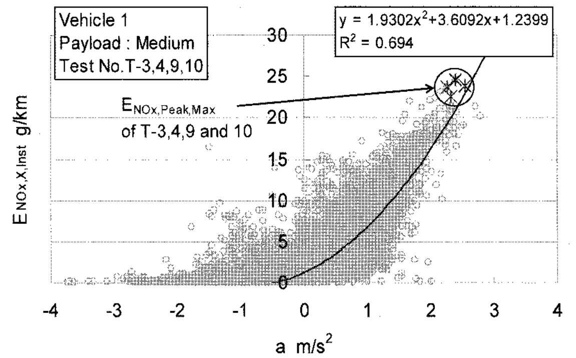

Figure 6. Relationship between vehicle acceleration and NOx emission factor.

partial clutch engagement condition were excluded in the result. The maximum value of instantaneous NOx emission factor of the second gear was highest in the all gear positions, and that of the higher gear became smaller. All of the maximum levels of NOx emission peaks of T-3, 4, 9 and 10 were caused when using of the second gear.

3.2.4. Relationship between vehicle acceleration and NOx emission factor

The relationship between vehicle acceleration and instantaneous NOx emission factor was analyzed.

Instantaneous NOx emission factor became larger by increasing vehicle acceleration as shown in Figure 6. All of the maximum levels of NOx emission peaks of T-3, 4, 9 and 10 were caused at the highest vehicle acceleration.

4. INFLUENCE OF OPERATION PATTERNS ON NO_X EMISSION PEAKS

From the above mentioned analyses, it is expected that low acceleration driving in the second gear position on road can improve the maximum level and frequency of NOx emission peaks. Therefore an additional road test of

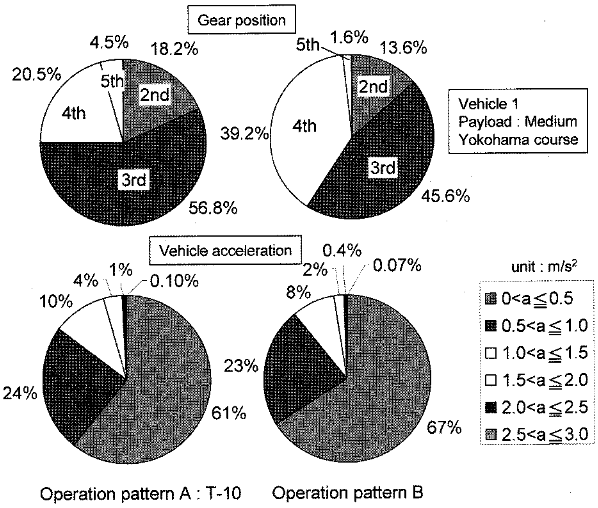

Figure 7. Operation patterns of Vehicle 1.

Vehicle 1 was conducted under medium payload condition in Yokohama course. The operation pattern of T-10 is defined as the operation pattern A, and that of the additional test which the test driver takes care to shift up at possible low speed and to accelerate vehicle slowly is defined as the operation pattern B in this research. The frequency of gear positions and accelerations are compared in Figure 7. The use of the neutral gear position and the vehicle deceleration condition were excluded in the results. The frequency of the second gear of the operation pattern B decreased by 4.6 points as compared to that of the operation pattern A. In addition, the frequency of the lowest acceleration less than 0.5 m/s^2 increased by 6 points as compared to that of the operation pattern A.

Figure 8 shows the change history of NOx emission peaks of the operation pattern B at Kizuki intersection described in Figure 3, which is the main intersection in Yokohama course, in comparison with that of the operation pattern A. The operation pattern B that consists of shifting up at lower engine speed in combination with lower vehicle acceleration reduced by 46% of a NOx emission peak in this example.

Table 8 shows the summary of the test results for the different operation patterns in Yokohama course. The operation pattern B reduced not only the maximum level and frequency of NOx emission peaks but also the

Table 8. Summary of test results for the different operation patterns in Yokohama course.

Operation pattern	V_{TR} (km/h)	$E_{NOx,X,TR}$ (g/km)	$E_{NOx,Peak,Max}$ (g/km)	$N_{NOx,Peak}$ (km^{-1})	$E_{CO2,X,TR}$ (g/km)
A: T-10	13.6	2.62	23.9	8.29	335
B	15.3	2.01	20.0	5.31	285

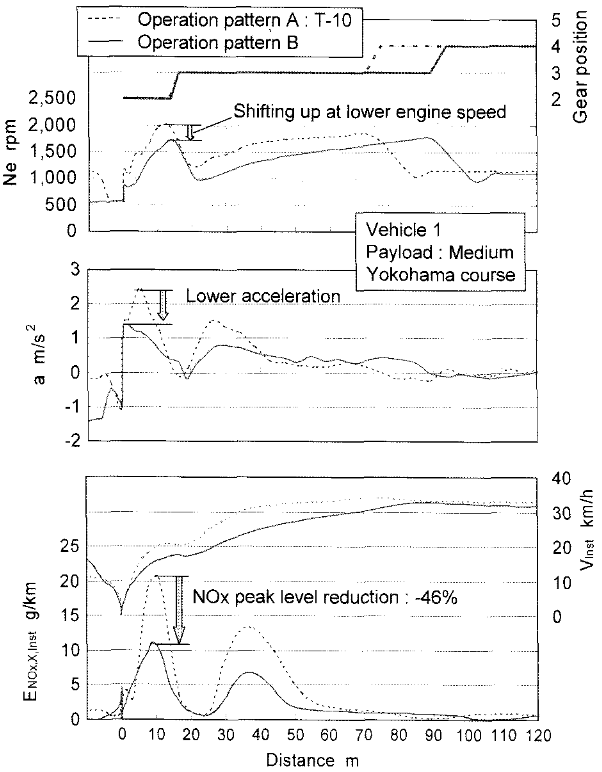

Figure 8. Influence of operation patterns on NOx emission peaks.

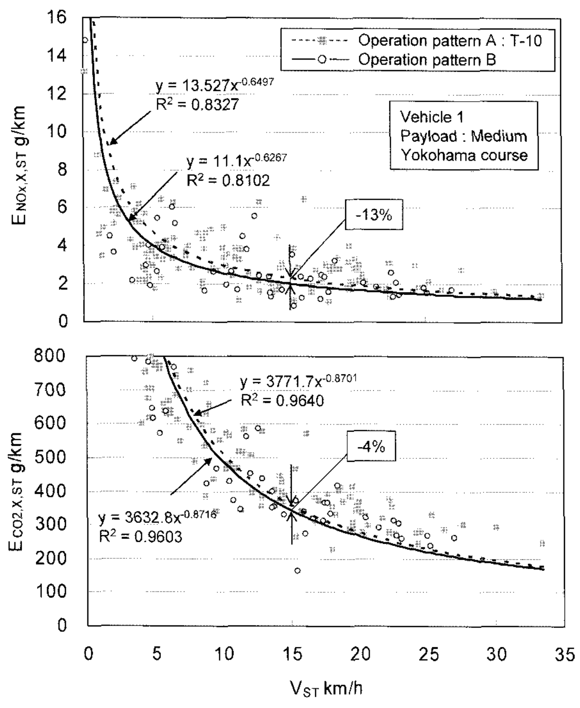

Figure 9. Average vehicle speed in each short trip versus NOx emission factor and CO_2 emission factor.

amount of NOx and CO_2 emissions through the entire course. However the evaluation for the amount of NOx and CO_2 emissions may be unfair because of a little bit higher average vehicle speed of the operation pattern B.

Therefore the short trip analysis was performed in order to clarify the relationship between the vehicle speed and the emissions factors. A short trip is defined as a section between the vehicle start and stop including idling condition in this study. The result is shown in Figure 9. The operation pattern B reduced by 13% of NOx emission factor and by 4% of CO_2 emission factor at 15 km/h of the vehicle speed as compared to those of the operation pattern A. Thus sifting up at lower engine speed in combination with lower vehicle acceleration brought out not only improvement of local roadsides air pollution but also reduction of the amount of exhaust emissions for a large area.

5. CONCLUSIONS

The evaluation of NOx emission peaks in real traffic conditions with an on-board measurement system was carried out with two types of light duty freight vehicles which have different emission levels. As a result, the followings were clarified.

(1) Many NOx emission peaks occurred when vehicle starting or acceleration at intersections, and the maximum level of NOx emission peaks reached more than 10 times as much as the average value of the test course.
(2) The maximum level and frequency of the NOx emission peaks of Vehicle 2 were higher than those of Vehicle 1.
(3) Shifting up at lower engine speed in combination with lower vehicle acceleration brought out not only improvement of local roadsides air pollution but also reduction of the amount of exhaust emissions for a large area.

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Appendix 1. Notations, units and meanings related to emissions and vehicle conditions.

Notation	Unit	Meaning
$E_{NOx,\ Peak,Max}$	g/km	Maximum level of NOx emission peaks
$E_{NOx,X,TR}$	g/km	NOx emission factor in the specified trip
$E_{NOx,X,Inst}$	g/km	Instantaneous NOx emission factor
$E_{NOx,X,ST}$	g/km	NOx emission factor in a short trip
$N_{NOx,Peak}$	km^{-1}	Number of NOx emission peaks per a kilometer
$E_{CO2,X,TR}$	g/km	CO_2 emission factor in the specified trip
$E_{CO2,X,ST}$	g/km	CO_2 emission factor in a short trip
V_{INST}	km/h	Instantaneous vehicle speed
V_{TR}	km/h	Average vehicle speed for the specified trip
V_{ST}	km/h	Average vehicle speed for a short trip
Ne	rpm	Engie speed
a	m/s^2	Vehicle acceleration
GVW	kg	Gross vehicle weight
VW	kg	Vehicle weight